

UNMANNED TRACKED GROUND VEHICLE FOR NATURAL ENVIRONMENTS

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ABSTRACT

The deployment of an autonomous and teleoperated vehicle in tropical environments presents numerous challenges due to the extreme conditions encountered. This paper presents the transformation of a M113 Armoured Personnel Carrier into an autonomous and teleoperated vehicle for operation in jungle-like conditions. The system was partitioned into functional systems: Vehicle Control/Mobility, Piloting, Visual Guidance, Teleoperation and Communications. Details of the system architecture and major components are included. Emphasis is made on the perception mechanisms developed for visual guidance, the vehicle conversion into a computer-controlled system and the implementation of navigation algorithms for localisation and path planning. A suite of onboard active and passive sensors is used in the visual guidance system. Data fusion is performed on the outputs of the different types of the sensors. The fusion result fed to the path planner that generates heading and speed commands to manoeuvre the vehicle towards the desired position. The vehicle controller executes the speed and heading commands and ensures the vehicle fast and safe response. The results from field trials completed in tropical forest conditions that are unique to the region are included.

1. INTRODUCTION

There has been a growing interest in the use of autonomous ground vehicles for defence related operations. Efforts have been led notably by the Future Combat Systems initiative in the USA. Whilst much progress has been achieved and several prototypes demonstrated, the applications are mainly under the environments where continental weather prevails, vegetation is light, and ground conditions are homogeneous. There is limited experience on the deployment of such vehicles in jungle like surroundings where high-density vegetation and changing light

conditions prevail, the tree canopies block GPS signals, and the ground is subject to fast deterioration under tropical rains [1], [2]. Platforms commonly used for autonomous vehicles in off-road applications are wheeled vehicles, like HMMWV in NavLab, the Red Team Consortium, or purpose-built platforms like in Demo III or the plethora of wheeled platforms fielded with a low success-rate, for the DARPA sponsored autonomous vehicle Grand Challenge race [2], [18]. There are few examples of tracked vehicles with autonomous capabilities, an exception is the Weasel light tracked armoured military vehicle used in the PRIMUS program (EADS-Germany), which is road-certified as a drive-by-wire vehicle [4].

Several defence organisations have a large stock of relatively outdated but operational vehicles. These, if transformed into unmanned units, could be deployed at marginal costs as surveillance platforms or for logistic purposes in hazardous areas. The design and commissioning of an Autonomous Unmanned Ground Vehicle (AUGV) is presented in this paper. This AUGV uses an M113 Armoured Personnel Carrier (APC) as the platform for this development. The unit is to operate under autonomous and teleoperated control during day and night conditions in jungle environments. The research and engineering challenges found are very different to those encountered elsewhere due to the extreme conditions to which it is exposed.

The context and system architecture are presented in Section 2 plus a description of the major components. Section 3 includes details of the perception mechanisms used for vehicle guidance. Section 4 describes the conversion of the vehicle onto a computer-controlled unit. Section 5 presents the Piloting component of the AUGV; this consists of the navigation components, namely, localisation, path planning and the supervisory control modules. The components developed as part of the Teleoperation Control System are presented in Section 6. The results obtained from vehicle trials are included and discussed in Section 7. Finally, the findings and lessons

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learnt from the deployment of this AUGV in a tropical environment are presented.

2. CONTEXT AND SYSTEM DESIGN

The environment consists of dense bushes or rows of trees surrounding non-tarmac roads and open spaces. The ground is covered with light gravel, tarmac and mainly light clay-type sand. Tree canopies attenuate GPS satellite signals. Light conditions constantly change and are subject to the density of the surrounding flora or weather conditions. Tropical rain transforms very rapidly the ground into a muddy terrain forcing the vehicle to skid as it travels. Figure 1 shows pictures that reflect the operating terrain conditions.



Fig. 1 Scenarios from the operational environment

The AUGV is based on a M113 APC, a skid-steer tracked vehicle. This is driven using brake levers that when pulled by the driver control the vehicle heading; there is a separate accelerator pedal and a semi-automated gearbox. In this design, the platform mobility will be considered as a system commanded in heading and speed, with a control module ensuring that the platform moves with the desired response. A basic requirement for this AUGV is to move autonomously on off-road environments or on non-tarmac roads at speeds up to 18 km/h during day conditions. At night, it is to move in the same environment but at lower speeds. Other functions,

include vehicle following and teleoperation. [7], [8].

For the vehicle to move autonomously, several functions are required: Perception provides information on the scene in front of the vehicle and to determine the traversable and non-traversable areas. Localisation determines the vehicle pose (position and orientation) with respect to a universal navigation frame. Mobility control ensures the vehicle response to velocity and heading commands. Navigation determines the vehicle heading and speed to direct it towards the goal position through areas determined by the perception and localization functions. Supervisory Control coordinates timely operations of all the system functions and transmits the target positions. Teleoperation enables a remotely located operator to manoeuvre the vehicle.

The block diagram in Figure 2 shows the modules and systems comprising the autonomous vehicle system plus their interrelationships. There are five systems; which can be described as follows:

- *The Visual Guidance System (VGS)* comprises a collection of active and passive sensors and a sensor fusion module. It generates an occupancy map representing traversable areas in front of the vehicle hence free of obstacles. Information used for obstacle avoidance and planning.
- *The Vehicle Piloting System (VPS)* governs the vehicle behaviour and determines the heading and speed needed to move the vehicle towards the target position. The path planning, localisation and coordinator-supervisory modules are part of this system.
- *The Vehicle Control System (VCS)* converts the vehicle into a computer-controlled platform, ensures the vehicle mobility and safety. It comprises the actuators moving the command levers, accelerator and gearbox lever, the vehicle control algorithm, and the safety mechanism.

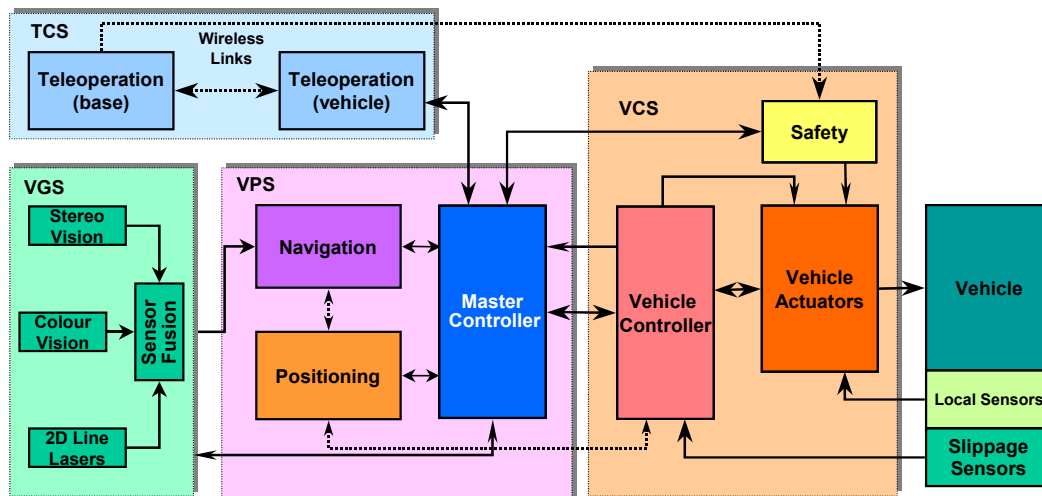


Fig.2 System Block Diagram

- *Teleoperation Control System (TCS)* enables a remotely located operator to control the vehicle using video signals received from the onboard cameras. It is used for telemetry and to command the various AUGV operating modes.
- *The Communications System (CS)* provides the means to transfer messages between the processes, running in multiple computers via an Ethernet network. It includes, a wireless communications link for teleoperation and telemetry purposes.

When operating as an autonomous vehicle, the system has three feedback control loops. The inner loop is formed by the servomechanisms acting on the brake levers and accelerator, a middle loop that ensures that the vehicle responds to the desired heading and speed commands despite changes to ground and vehicle conditions. The vehicle pose and dynamics provide feedback. The outer loop is closed by the path planner that commands the vehicle as a function of the target position (the set-point), the vehicle pose and the traversable areas, as determined by the VGS sensors.

3. AUGV IMPLEMENTATION

The implementation details are presented in this section with emphasis on the resulting vehicle layout, the visual guidance, vehicle control, piloting and teleoperation systems. This is presented with regard to the components used, algorithms developed and the manner in which they are integrated to make such a large unit to

navigate autonomously or under teleoperation in the jungle of Singapore.

3.1 AUGV Component Layout

The layout of all components was limited by the constraint that the vehicle should not be structurally modified and that it should still be possible for a driver to operate it or have precedence when the unit was under computer-control. There were limitations with respect to the height of antennas to no more than 3.2m. Physically the fixing of actuators to move the brake levers and accelerator was difficulty and the fixture needed special design. Another source of concern was available electrical power for actuators, computers, RF transmitters, etc. Figure 5 shows a CAD model of the M113 integrated with the guidance sensors used for autonomous and teleoperated operation, safety sensors, the location of the inertial measurement unit, as well as that of the actuating mechanisms in the driver compartment. It also shows the layout of the GPS, and RF antennas communications

The picture in Figure 6 shows the layout of the guidance sensors and communications units in the actual vehicle. Fixtures are of a temporary kind, they are used to support sensors for trials only. The vehicle can still carry a full crew; all computers are located to the side of the interior compartment and powered from a petrol generator.

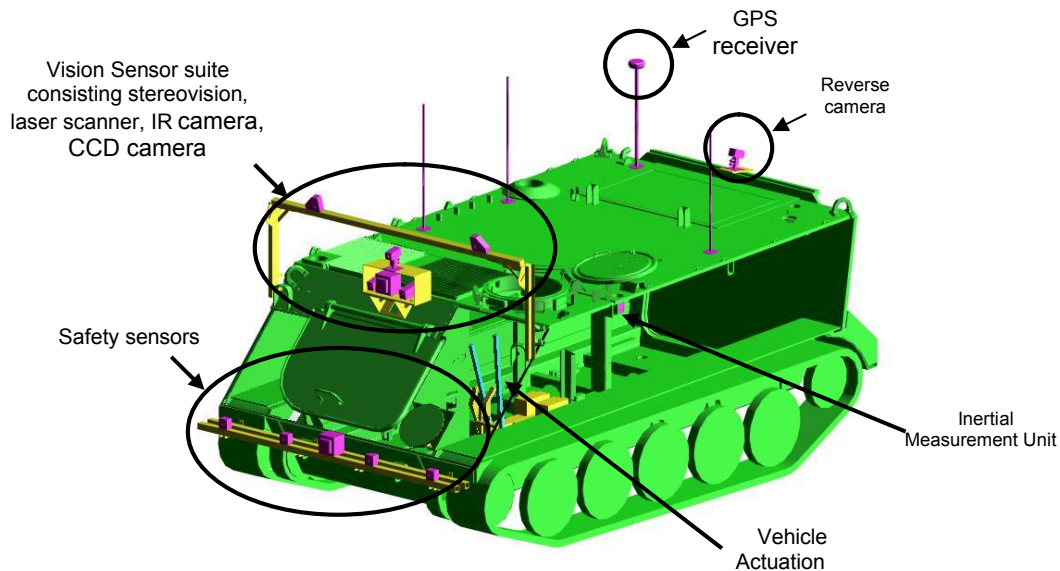


Fig. 5. CAD model of the AUGV M113 including sensors, actuators and communication antennas



Fig.6. The M113 APC integrated with sensors

3.2 Visual Guidance System

Jungle-like environments are distinctive, vegetation is dense and varied, there are randomly distributed trees, non-tarmac roads are surrounded by vegetation, there are dense tree canopies, etc. Therefore, vehicles have to traverse terrain under different light conditions and texture. In equatorial regions; it is common to have cloudy or sunny conditions within few hours. The terrain will quickly become unstable after torrential rain, thus the vehicle when travelling will tilt in all directions.

Data collection trials were performed initially using several sensors these included CCD cameras for stereovision and colour segmentation, 2D lasers for range measurement (obstacles), and an infrared cameras for night conditions. These were mounted on an experimental platform as shown in Figure 7, which was moved in the test area acquiring as much data as possible in different terrain and light conditions. The data was used to experiment with several algorithms and different combination of sensors as well as different fields of views.

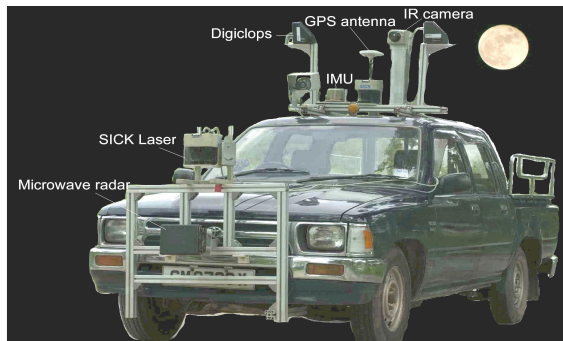


Fig. 7. Experimental Vehicle with Guidance Sensors

Results from the initial trials and system design considerations found in the literature were used to determine the VGS lookout view of 15m by 18m with a

resolution of 0.2m for guidance purposes [19], [20]. The system output is in the form of an occupancy (obstacle) map with the fore mentioned resolution at 5 Hz. The VGS consists of the stereovision, colour segmentation, 2D laser ranging and the sensor fusion modules. An infrared camera is used only for operation at night. The stereovision module generates a disparity map that it is used to estimate range from objects within the lookout view and to determine the presence of obstacles (objects larger than 0.4m in height and 0.4m in width). Two multibaseline trinocular stereovision cameras (PointGrey) are used to look into the first 12m. The narrow angle of view (12mm lens) means that two sets are required; their outputs are merged onto a single reference frame. The module generates slope information with a resolution of 1m; this information is fed to the piloting system to determine whether or not the areas to be traversed are too steep for the vehicle [11]. Figure 8 shows a sample output from the obstacle search grid, in the output of the stereovision cameras and the generated slope map.

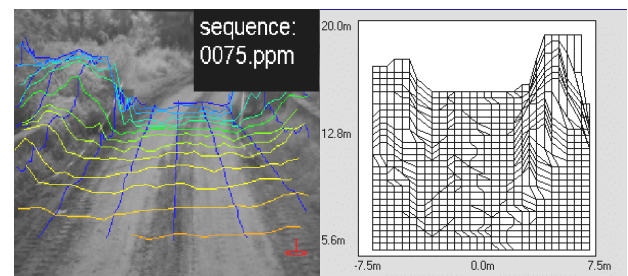


Figure 8. Outputs from the stereovision module

Variations of light conditions and texture at the test site are extreme, experiments demonstrated that the COTS stereovision used although rich in information, generated at times too many false alarms and several undefined areas; range was shorter than expected. To look beyond the 12 m limit and add more confidence to the detected obstacles, a pair of 2-D, single line laser range sensors (SICK GmBh) is used. These are

configured to sense up to 18m at a frequency of 20 Hz. One is located at the bottom part of the vehicle and the other on the roof looking downwards (c.f. Figures 5 and 6). Both generate a common occupancy grid with the same resolution as the stereovision module but at 20Hz.

As part of the design it was decided to drive whenever possible on non-tarmac roads whilst moving towards the goal position. For this purpose, another module was included that uses colour differences between roads (driveable) and vegetation (non-driveable). The function is to differentiate them and to determine the road centroids, which are sent to the path-planner as the preferred road that the vehicle should follow [12].

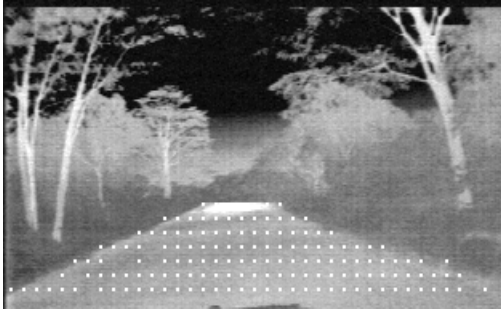


Fig. 9. Road Segmentation using IR cameras

For autonomous operation during night conditions the Indigo bolometer non-cooled long wave Infrared camera is used. By determining the typical temperature of the surrounding vegetation and measuring the temperature of the non-tarmac roads with the IR camera, it is possible to separate the acquired images into driveable and non-driveable areas. This is done through the use of filtering and image segmentation algorithms. Once the road is determined, and sent to the path planner. A typical segmented image obtained from this module is shown in Figure 9.

Results from the stereovision and laser modules are mapped onto a common sensor reference frame. Two sensor fusion methods are used, Opinion Pool for low underkill rate (missing a true obstacle) and feature registration for low overkill rate (false alarm). The output from the laser and stereovision modules are merged for day operations whilst the IR camera module is used instead of the stereovision module for night operations. Sensor fusion is effected for IR and Ladar results.

3.3 Vehicle Control System

The VCS converts the manually driven M113 into a computer-controlled unit. It consists of servomechanisms, the vehicle controller and the safety mechanism. The M113 is entirely mechanically controlled. For manual driving, a driver controls the vehicle heading by operating left or right brake levers that slow down the corresponding tracks to turn the vehicle left or right. The vehicle is stopped when both levers are applied. A control system was developed, comprising servo-actuators to control the steering levers and accelerator

pedal, and a higher-level controller to ensure the vehicle response to heading and speed commands.

Extensive trials were performed to characterise the vehicle dynamics, the actuation properties and actuation forces required. It was found that the controlling mechanisms are highly non-linear. For example experiment data of the brake lever position and applied lever force plotted in Figure 10 shows that forces are varied for the same brake lever position. Based on statistics, a non-linear curve representing the relationship between the brake force and the brake lever position is generated. This was used for steering control. Another major controller challenge is the wide dynamic range required due to the terrain topography and vehicle weight.

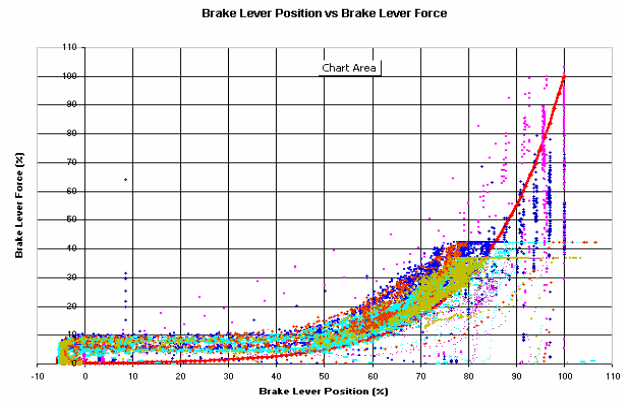


Fig. 10. Test Results on Brake Forces

The layout of the servomechanisms inside the driver compartment to actuate the brake levers and the accelerator pedal are shown in Figure 11. Their motion imitates that of a driver and provides actuation to manoeuvre the vehicle under computer-control. A MIMO control algorithm is implemented; its inputs are the desired vehicle heading and speed and outputs commands to various actuators. It is based on a PID-based controller, with adaptive control parameters, heuristic switching, and non-linearity compensation [10]. The algorithm is implemented on a PC-104 type computer. Communication links with the actuation module are via a CAN-bus and with the rest of the system via an Ethernet network. Details on the drive-by-wire implementation can be found in [10].

A set of ultrasonic sensors plus radar act as a virtual bumper that will trigger alarm signals that will force the actuation servomechanisms for the brake levers to bring the vehicle to a halt. Perhaps add LASER part here.

3.4 Vehicle Piloting System

The VPS allows the AUGV to navigate from point to point, and avoid obstacles in the process. This is performed by the navigation module or path-planner. For the vehicle to reach its destination it must know its location, information provided by the Positioning

Module. For all modules to operate in a synchronized manner and to monitor their status a supervisory-master controller based on state-diagrams was implemented.

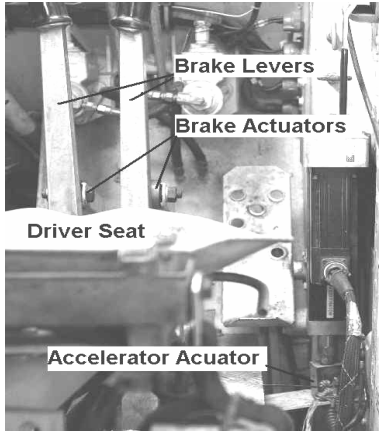
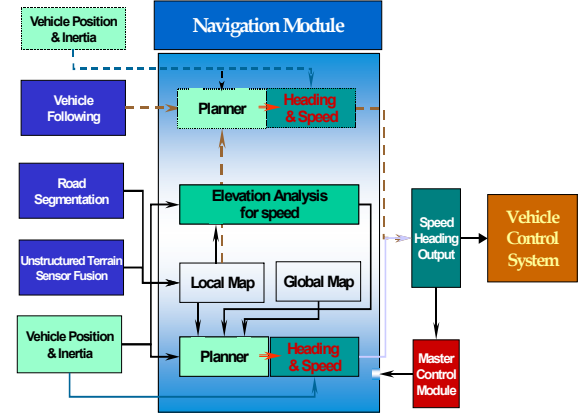


Fig. 11. Layout of actuators inside the driver compartment

The estimation of the vehicle pose (position, velocity and attitude) with respect to a universal navigation frame is made through the combination of low-frequency GPS with high-frequency Inertial Measurement Unit (IMU) information. Data from the IMU is used to estimate the vehicle pose using an Inertial Navigation System (INS) algorithm. To compensate for INS errors due to biases, drift and random walk errors originated in the IMU, a Kalman Filter that uses GPS measurement estimates and INS errors to correct the INS estimation algorithms is integrated. Thus, when a GPS fix is obtained, an observation is evaluated and the filter then estimates the errors produced by the INS, these are used to correct the INS. A low-cost IMU from Inertial Science Inc., a GPS from Thrimble and an electronic compass from PNI Corp. are used in this module. The compass is used for initialisation purposes. The software runs on a PC-104 type computer under the QNX operating system. The vehicle pose information is generated at 20 Hz and distributed at different rates to other system modules. The path-planner determines the trajectory to be followed by the vehicle from its start position to the desired target. The estimated speed and heading commands are based on the occupancy map generated at the VGS, the current vehicle pose and dynamic constraints. The algorithm uses the modified distance-transform plus a vector histogram for path-planning. This generates a collection of desired points towards which the vehicle should move [13]. These are used as inputs to another algorithm that applies the vehicle total energy principle to derive a control law that incorporates the physical bounds of the vehicle dynamics and generates the heading and speed commands to the vehicle controller [14].

The structure of the navigation module is shown in Figure 12. The planner to generate the vehicle trajectory uses both a global and a local map. In addition it uses when available information of the road centroids to bias the vehicle trajectory towards detected roads. It then executes a terrain traversability test based on an elevation



analysis of the slope information generated by the VGS. Feedback is provided in the form of the vehicle pose and dynamics.

Fig. 12. Architecture of navigation module

3.5 Teleoperation Control System

The TCS consists of two major components: The first resides on the AUGV and comprises a camera mounted on a pan & tilt mechanism for remote driving, a video transmitter, RF modems, and antennas plus a computer for communications purposes and control. The second comprises an Operator Control Unit (OCU), a video receiver and RF modems plus a set of antennas forming the base station. The OCU issues commands to the AUGV via the RF modem, and receives status feedback from the AUGV. Live video from the AUGV onboard cameras is also transmitted to the OCU via the video RF link. The operator at the OCU is able to change the vehicle operating modes (autonomous, teleoperation). It is also possible to control various vehicle functions such as lights, horns, etc. Operator feedback and interaction is provided via a touch screen, joystick levers, and push buttons. At the TCS, capabilities for performing waypoint navigation were incorporated. These allow remote control of the vehicle using still images and utilizing the obstacle avoidance capabilities of the navigation module to move the vehicle on a stop-go basis when video signals are not available.

Figure 13 shows details of the operator interface. The display is partitioned into zones for the live video display, vehicle status information, communication links, a scalable map and mode-specific control panels [7].



Fig. 13. Operator Interface.

4. . RESULTS

The AUGV was tested in the scenarios shown in Figure 1. The extreme environmental conditions encountered proved to be more difficult than expected whilst controlling indirectly the vehicle through the actuating mechanisms introduced unwanted delays into the system control loop. Extensive tuning was needed for the navigation, controller and perception modules. There was much vehicle vibration, abundant dust, the vehicle could tilt more than 15 degrees on a believed flat terrain, and tropical rain would deteriorate roads very rapidly; the addition of these factors caused several problems. During tuning, the guidance sensors will produce multiple false alarms, some low-height obstacles will be missed by the lasers as they will be pointing to the wrong direction due to the vehicle orientation (tilt), cameras will become saturated due to changes in light conditions, etc. These required much work on the sensor fusion and path-planning algorithms as well as sensor modules.

The resulting system could navigate from a start position to a target location given a set sparsely distributed control waypoints, traversing terrain which included slopes, narrow passages and obstacles distributed as for a slalom-like trajectory. A typical obstacle map generated by the VGS and used for planning purposes together with the plotted vehicle trajectory is shown in Figure 14. The detected obstacles are grown to take into account the vehicle width plus a safety buffer zone that is varied according to the vehicle speed and obstacle density found. The expected trajectory from the mission waypoints and the trajectory traversed by the vehicle are plotted. The interface allows developers to record and replay the entire vehicle trajectory from the obstacle map point of view and has been very useful during the commissioning phase. In a typical test environment that includes high-density vegetation, sharp corners and irregular terrain due to seasonal rain, the AUGV reached a maximum speed of 15.8 km/h with an average speed of 13.5 km/h over a distance of 1.8 km (test areas are small). The recorded vehicle trajectory is plotted in Figure 15. It shows the behaviour of the vehicle and the oscillations occurred at certain points due to the presence of false obstacles or delays in the vehicle response.

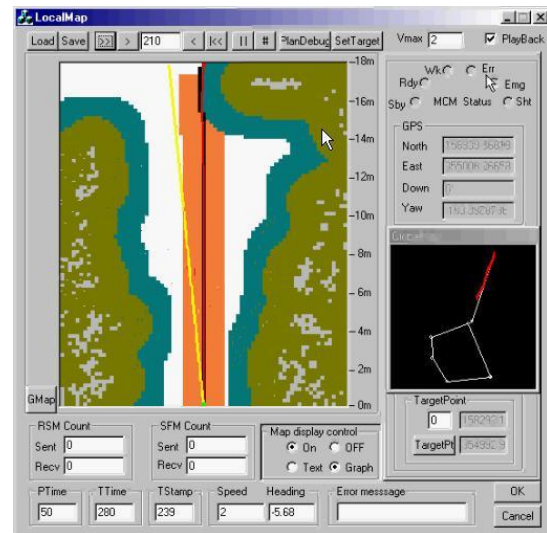


Fig. 14. Recorded local obstacle map and on-line planned trajectory

The tests conducted at night were made in areas with more open spaces and at reduced speeds for safety. For these, the vehicle is configured to use the laser range sensors and IR camera. The distances travelled in autonomous mode were around 1.7 km at a maximum speed of 11 km/h. Jungle conditions are such that there is no reversal of temperature, simplifying the road segmentation algorithms complexity.

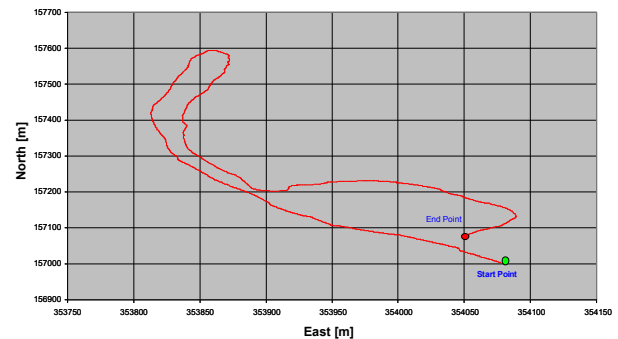


Fig. 15 Typical vehicle trajectory during tests

In the test conditions, sensing uncertainty, vehicle response, and the limited field of views reduced the speed at which the platform could be moved, the platform. In addition, the system had to endure intensive heat and humidity that reduced the performance of on board computers and sensors.

CONCLUSIONS

Unmanned navigation for M113 APC was demonstrated; it included autonomous navigation, road and vehicle following (platooning), and teleoperation capabilities. Whilst speeds attained are low for operational purposes and with respect to similar programs, two basic considerations need to be taken: The mechanical manner in which the computer-control of this relative old APC was implemented to circumvent

modifications to the vehicle, and the extreme conditions found in jungle environments. The demonstrator has enable us to show that a relatively old APC can be converted into an AUGV as well as to perform pioneering work on autonomous driving in the jungle conditions.

The development of this unique autonomous system was presented, all system components were described and algorithms used named. The implementation has resulted in the development of our own architecture for autonomous systems. Through the use of multiple sensors for visual guidance it was possible to compensate for their limitations in terms of range, certainty and response. The development of a control module to command the vehicle in terms of heading and speed was the correct choice, to compensate for the cognitive abilities of a human driving such a mechanically commanded machine. The inclusion of the vehicle dynamics in the planning module, allowed us to command the vehicle within its dynamic capabilities.

The maximum attained speed was 18 km/h on straight roads, this was limited by: The vehicle response which becomes nervous at high speeds, small changes or delays will veer the vehicle from the intended trajectory, and the semi-automatic gearbox will change suddenly modifying the system response. The sensors FOV need to be extended for the vehicle to move at higher speeds with improvements to the capabilities of the stereovision module in particular. Another issue was safety, a 12-ton mass moving at high speeds will store very high kinetic energy, stopping it takes almost 8m, failure to do so could cause a lot of damage, we have small test environments.

Whilst the results complied with the sponsor specifications, there are several pending research issues. These include use of probabilistic models to enhance world representation for vehicle guidance, situational awareness. The introduction of attributes into the occupancy maps for planning purposes, the use of an advanced terrain/soil driven vehicle controller, machine perception, and the introduction of survivability concepts to render the platform robust to the unexpected. To give applicability to this AUGV work on mission planning is needed for the deployment of payloads or multiple vehicles working in a coordinated manner. The results of the DARPA sponsored race on off-road autonomous vehicles have shown that autonomous driving in unknown environments remains a Grand Challenge.

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